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Waste Heat Dehumidification in CO_2 Booster Supermarket

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ABSTRACT

Carbon dioxide (CO_2) being a low Global Warming Potential (GWP) refrigerant is becoming a popular choice as an efficient refrigerant in supermarket refrigeration systems, not only in moderate climates such as Northern Europe but also in the United States. Due to its low critical temperature (31.06°C), CO_2 systems also offer potential for waste heat utilization. This paper, therefore, aims to uncover this potential for the US supermarket refrigeration industry through simulation. In this process, the whole building energy modeling tool, EnergyPlus, has been used to investigate the energy consumption of a supermarket utilizing packaged rooftop air conditioning units and a transcritical CO_2 booster refrigeration system. The potential for waste heat utilization for application in desiccant regeneration, water heating and space heating has been analyzed. In addition, the energy impact of humidity control within the supermarket on the HVAC system is investigated. Finally, the waste heat utilization potential of the transcritical CO_2 booster refrigeration system is compared with the baseline R404A multiplex direct expansion system in sixteen cities from eight climate zones of the United States.

1. INTRODUCTION

In an effort to reduce the greenhouse gas emissions of supermarket refrigeration systems, carbon dioxide (CO_2) has recently received considerable attention as an alternative to the high Global Warming Potential (GWP) synthetic refrigerants commonly used in supermarket systems (Bansal, 2012; Getu and Bansal, 2008). The benefits of carbon dioxide include no Ozone Depletion Potential (ODP), and a GWP value of one, as well as being nontoxic, nonflammable and inexpensive. Although CO_2 has a high critical pressure (7.38 MPa) and a low critical temperature (31.06°C), its high operating pressure leads to a high vapor density, and thus a high volumetric refrigerating capacity. For example, the volumetric refrigerating capacity of CO_2 (22,545 kJ•m−3 at 0°C) is three to ten times larger than that of many CFC, HCFC, HFC and HC refrigerants (Kim et al., 2004).

Carbon dioxide has successfully been used as a refrigerant in the low-temperature circuit of cascade systems, in secondary loop systems, and in transcritical systems (Bansal, 2012; Hinde and Zha, 2009; Girotto et al., 2004). However, transcritical CO_2 systems tend to be more popular in moderate climates such as Northern Europe where the refrigeration system operates a majority of the time in the more efficient subcritical mode (Sawalha and Palm, 2003). A recent study by Sharma *et al*. (2014) indicated that the transcritical CO_2 booster system could perform well in the northern two thirds of the US.

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Due to its low critical temperature (31.06°C), CO_2 systems also offer potential for waste heat utilization. This paper, therefore, aims to uncover this potential for the US supermarket refrigeration industry through simulation. The whole building energy modeling tool, EnergyPlus, will be used to simulate the energy consumption of a model supermarket in sixteen cities from eight climate zones of the United States. This model supermarket uses packaged rooftop air conditioning units and a transcritical CO_2 booster refrigeration system. The feasibility of a waste heat utilization scheme incorporating desiccant regeneration, water heating and space heating will be analyzed. The energy impact of humidity control within the supermarket on the HVAC system will also be investigated. Finally, the waste heat utilization potential of the transcritical CO_2 booster refrigeration system is compared with the baseline R404A multiplex direct expansion system.

2. BUILDING ENERGY MODELING

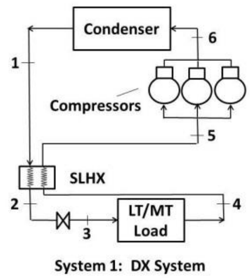
The EnergyPlus supermarket model used in this study was based on the new construction reference supermarket model developed by the U.S. Department of Energy (Deru et al. 2010). This model single-story supermarket has a floor area of 4,181 m^2 with a floor-to-ceiling height of 6.1 m, and is divided into six zones (office, dry storage, deli, sales, produce and bakery). Exterior wall construction consists of stucco, concrete block, insulation and gypsum while roof construction consists of roofing membrane, insulation and metal decking. Internal loads include people and lighting, as well as miscellaneous gas and electric loads in the deli and bakery zones. HVAC is provided by packaged constant volume units with gas heat and electric cooling. In addition, to investigate the potential for waste heat utilization for application to desiccant regeneration, desiccant dehumidification and humidification are used to maintain the relative humidity within the supermarket at either 30% or 55%. For the model supermarket, the total refrigeration loads from the medium-temperature and low-temperature display cases and walk-ins are 220 kW and 88 kW, respectively. Finally, to determine the significance of climate on waste heat recovery potential, the energy consumption of the model supermarket was estimated for 16 U.S. cities using EnergyPlus. These 16 cities, shown in **Table 1**, are representative of the eight climate zones in the U.S.

Table 1: Climate zones and cities used in the waste heat utilization analysis

Climate Zone	City	Annual Average		Climate Zone	City	Annual Average	
		Temper-ature (°C)	Relative Humid-ity (%)			Temper-ature (°C)	Relative Humid-ity (%)
1A	Miami, FL	24.9	72.6	4B	Albuquerque, NM	14.2	42.4
2A	Houston, TX	20.7	73.0	4C	Seattle, WA	11.4	74.3
2B	Phoenix, AZ	23.8	34.2	5A	Chicago, IL	10.0	70.3
3A	Atlanta, GA	17.0	65.7	5B	Boulder, CO	10.3	51.3
3B	Los Angeles, CA	17.3	73.0	6A	Minneapolis, MN	8.0	65.7
3B	Las Vegas, NV	20.2	29.6	6B	Helena, MT	7.2	57.9
3C	San Francisco, CA	14.4	74.5	7	Duluth, MN	4.3	71.6
4A	Baltimore, MD	13.3	64.6	8	Fairbanks, AK	-2.1	67.8

3. REFRIGERATION SYSTEM DESCRIPTIONS

In this paper, two different commercial refrigeration systems are investigated which serve the medium- and low-temperature loads of the model supermarket discussed above. The first system, the baseline system, is a typical multiplex direct expansion (DX) supermarket refrigeration system using R-404A as the refrigerant. The second system is a natural refrigerant system in which carbon dioxide is used in a transcritical booster configuration. Schematic diagrams and p-h diagrams for these two refrigeration systems are shown in **Figure 1** and **Figure 2**, respectively.



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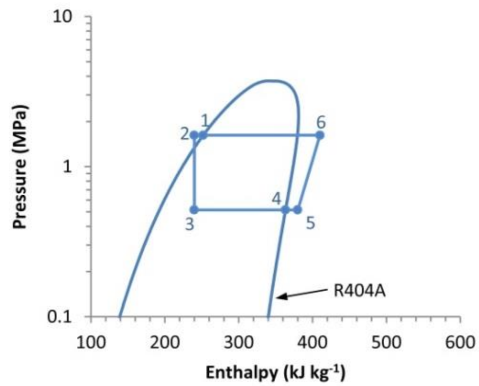

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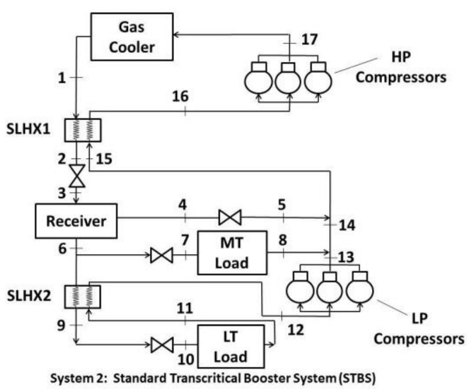
Figure 1: Multiplex direct expansion (DX) system: (a) Schematic, and (b) p-h diagram



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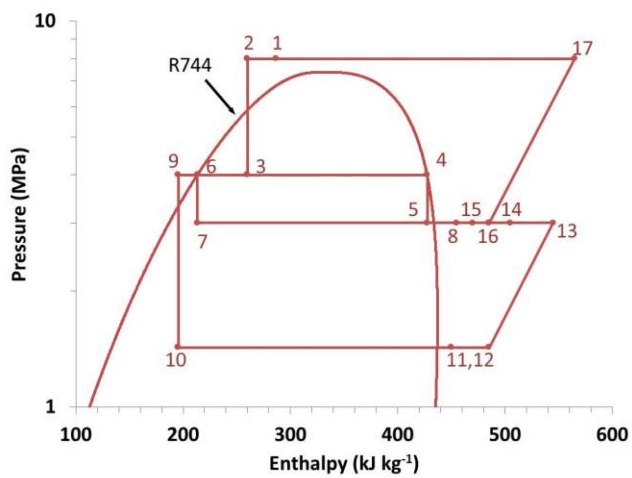

(b)

Figure 2: Transcritical CO_2 booster system: (a) Schematic, and (b) p-h diagram

3.1 Multiplex Direct Expansion (DX) System

For this analysis, it was assumed that the multiplex DX system consisted of two separate compressor racks: one serving the medium-temperature loads and the other serving the low-temperature loads. Each compressor rack was connected to its own dedicated air-cooled condenser. The medium-temperature saturated suction temperature was fixed at −5°C while the low-temperature saturated suction temperature was fixed at −30°C. A 10 K temperature difference was maintained between the saturated condensing temperature and the ambient air, with a minimum condensing temperature of 21°C. In addition, no subcooling was assumed to occur at the condenser outlet.

3.2 Standard Transcritical Booster System (STBS)

When the compressor discharge conditions are such that the CO_2 is in the supercritical region, then the high-side operating pressure is independent of the gas cooler exit temperature (Sawalha, 2008). Thus, for a given gas cooler exit temperature, there is an optimum pressure to achieve the maximum coefficient of performance (COP). Several researchers have developed correlations to determine the optimum high-side pressure in transcritical R744 refrigeration systems. The refrigeration system energy simulation assumed system operation at optimal gas pressure control.

During transcritical operation, the gas cooler approach temperature, which is the difference between the gas cooler outlet temperature and the ambient air temperature, was set to 3°C. During subcritical operation, the temperature difference between the saturated condensing temperature and the ambient air temperature was set to 10 K, and the minimum condensing temperature was assumed to be 10°C. Furthermore, no subcooling was assumed to occur at the outlet of the condenser during subcritical operation and the pressure in the receiver was fixed at 3.5 MPa. The saturated suction temperature for the medium-temperature loads was fixed at −5°C while for the low temperature loads, the saturated suction temperature was fixed at −30°C. Finally, a superheat of 10 K was used at the exit of the evaporators.

4. WASTE HEAT UTILIZATION

When a CO_2 refrigeration system operates at subcritical pressure, the heat rejection from the system occurs at a constant temperature (after desuperheating the compressor discharge gas). However, at supercritical pressure, the heat rejection from a CO_2 refrigeration system occurs over a range of temperature, rather than at a constant temperature. Thus, the average heat rejection temperature is higher for supercritical operation than for subcritical operation, making supercritical operation more suited to heat recovery applications.

To investigate the heat recovery potential from CO_2 refrigeration systems, an analysis was performed in which the heat rejected from the system is used for desiccant regeneration, water heating and space heating. In this study, the whole building energy simulation program, EnergyPlus, was used to determine the hourly space heating, water heating and desiccant regeneration heating needs of a supermarket for a period of one year in 16 cities in the United States, representing eight climate zones. Two levels of humidity within the supermarket were considered: 55% RH and 35% RH. The energy which could be recovered from a transcritical CO_2 refrigeration system was then compared with the heating needs of the supermarket to determine the potential that heat recovery could be used to offset the heating requirements of a supermarket. In addition, the heat recovery potential of the transcritical CO_2 booster system was compared to the baseline R-404A multiplex DX refrigeration system for the case of maintaining store humidity level at 55% RH.

Figure 3 shows a schematic of the hypothetical three-stage heat recovery scheme investigated in this study. Waste heat from the refrigeration system is first used to heat regeneration air for the desiccant dehumidifier. The source of the regeneration air is the ambient, and this air is heated to a maximum temperature of 120°C. Next, the waste heat is used to heat water for process applications. It was assumed that water entered the supermarket at 10°C and was heated to a maximum of 60°C. Finally, the remaining waste heat is used for space heating, where it was assumed that the supply air (ambient air) would be heated from ambient temperature to a maximum of 40°C.

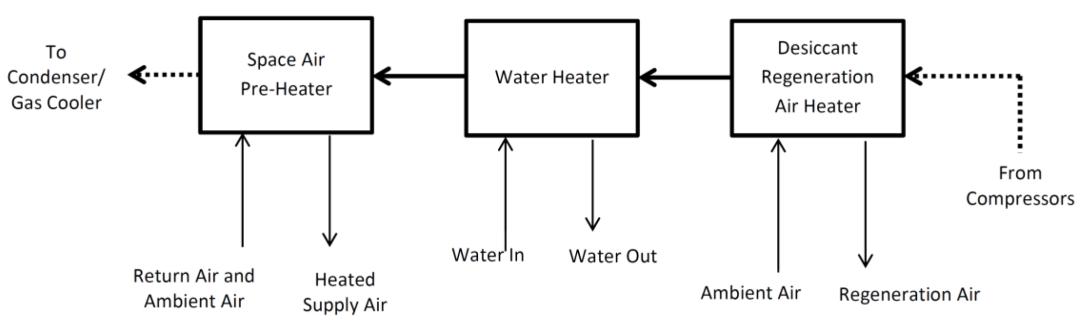

Figure 3: Waste heat utilization scheme

5. RESULTS

The results of the waste heat utilization analysis for the transcritical CO_2 booster system are summarized in **Table 2**. For each city and use category (i.e., desiccant regeneration, water heating, or space heating), the percentage of the use category's energy needs met by waste heat recovery is listed for store ambient humidity of 35% and 55%. In general, the ability of waste heat recovery to satisfy supermarket water heating and space heating requirements decreases from the warmer climate zones to the colder climate zones. Lower grade waste heat is generated by the refrigeration systems in colder climates due to their lower average condensing temperatures. It can also be seen that the ability to recovery waste heat for desiccant regeneration is a function of both the annual average temperature and the annual average humidity of the supermarket's location. Cities with high temperature and low humidity are able to satisfy desiccant regeneration loads more readily than cities with higher humidity.

Table 2: Results of waste heat utilization analysis for transcritical CO_2 booster system

Climate Zone, City	Desiccant Regeneration (DR)		Water Heating (WH)		Space Heating (SH)	
	% of DR Load Met by Waste Heat Recovery		% of WH Load Met by Waste Heat Recovery		% of SH Load Met by Waste Heat Recovery	
	35% RH	55% RH	35% RH	55% RH	35% RH	55% RH
1, Miami	51.6	60.9	84.9	93.9	39.3	64.7
2A, Houston	54.1	62.9	86.7	95.5	36.8	52.8
2B, Phoenix	75.7	77.2	97.9	99.4	58.7	60.6
3A, Atlanta	54.6	64.1	87.1	94.2	31.7	41.2
3B, Los Angeles	51.9	59.9	83.1	99.0	37.5	69.0
3B, Las Vegas	79.6	87.9	97.2	97.7	45.3	44.9
3C, San Francisco	67.5	94.1	79.0	99.0	30.1	48.7
4A, Baltimore	54.5	62.5	85.1	90.3	24.7	28.7
4B, Albuquerque	12.6	60.1	92.1	92.9	32.4	32.5
4C, Seattle	53.9	59.3	85.1	93.1	24.5	29.5
5A, Chicago	54.6	63.6	80.8	85.9	18.9	22.0
5B, Boulder	64.8	64.9	88.5	89.0	25.9	26.0
6A, Minneapolis	55.8	64.8	80.2	83.6	16.6	18.0
6B, Helena	63.6	--	84.0	84.5	19.3	19.6
7, Duluth	52.3	60.8	77.1	81.0	13.8	15.5
8, Fairbanks	10.1	59.0	76.6	78.2	10.5	11.0

5.1 STBS Heat Recovery for Store Humidity of 55%

For all climate zones with store humidity of 55%, it can be seen that, on average, approximately 67% of the energy required for desiccant regeneration can be obtained through waste heat recovery. The heat required for desiccant regeneration is only a small fraction of the total heating requirement for the supermarket, where desiccant regeneration represents approximately 7% of the total heating requirement for the 16 cities.

For 55% relative humidity within the store, it can be seen that the greatest percentage of heat recovery for desiccant regeneration occurs in the cities with the warmest climates and the lowest humidities (Phoenix and Las Vegas). San Francisco, with a lower annual average temperature and higher annual average humidity than Phoenix or Las Vegas, also had a high percentage of heat recovery for desiccant regeneration. The percentage of desiccant load met by waste heat recovery was over 77% for these three cities. Note that the annual average temperature of San Francisco and Albuquerque are nearly the same while the annual average humidity of San Francisco is significantly higher than that of Albuquerque (74.5% vs 42.4%). However, the CO_2 system manages to satisfy 94% of the desiccant regeneration load in San Francisco compared to only 60% in Albuquerque. This is due to the narrower range of annual ambient temperature in San Francisco (standard deviation = 6.9°C) as compared to Albuquerque (standard deviation = 17.9°C). The percentage of the desiccant load met by waste heat recovery for the remaining cities was in the range of 59% to 65%.

For Climate Zones 1 through 4 with store humidity of 55%, over 90% of the water heating needs of the supermarket can be met through waste heat recovery. For the colder climate zones (Zones 5 through 8), waste heat recovery can contribute, on average, to 84% of the required water heating. Furthermore, the energy analysis indicates that water heating accounts for approximately 8% of the total heating requirement of a supermarket. Finally, it can be noted that waste heat recovery can contribute between 11% to 69% of the required space heating. The warmer climate zones tend to benefit from having more of the space heating load met by waste heat recovery compared with the colder climate zones. Also, space heating accounts for approximately 85% of the total heating requirement of a supermarket.

5.2 STBS Heat Recovery for Store Humidity of 35%

At store relative humidity of 35% for all climate zones, it can be seen that, on average, approximately 54% of the energy required for desiccant regeneration can be obtained through waste heat recovery, which is 13% lower than that for 55% RH. Desiccant regeneration represents approximately 18% of the total heating requirement for the 16 cities. Furthermore, the average desiccant heating required to maintain 35% store RH was nearly four times greater than that required to maintain 55% store RH.

For 35% relative humidity within the store, the cities with low average annual humidity exhibited the greatest percentage of heat recovery for desiccant regeneration. These cities include Phoenix, Las Vegas, Boulder and Helena. In addition, San Francisco also had a high percentage of heat recovery for desiccant regeneration. The percentage of desiccant load met by waste heat recovery was between 64% to 80% for these five cities. Albuquerque and Fairbanks exhibited the lowest heat recovery potential for desiccant regeneration, with only 10% to 13% of the desiccant regeneration load met. The remaining cities, which have high annual average relative humidities, extracted between 52% to 56% of their desiccant regeneration heating requirements from waste heat.

At store relative humidity of 35% for all climate zones, waste heat recovery can contribute, on average, to 85% of the required water heating, which is 5% less than that at 55% store RH. Furthermore, the energy analysis indicates that water heating accounts for approximately 7% of the total heating requirement of a supermarket. Finally, it can be noted that waste heat recovery can contribute between 11% to 49% of the required space heating, which is up to 20% less than that at 55% store RH. Also, space heating accounts for approximately 75% of the total heating requirement of a supermarket.

5.3 Comparison between R-404A DX and STBS

The comparison of the waste heat utilization analysis for the transcritical CO_2 booster system and the baseline R-404A multiplex DX system for the case of 55% RH within the store is summarized in **Table 3**.

Table 3: Comparison of waste heat utilization analysis for the transcritical CO_2 booster system and the baseline R-404A multiplex DX system

Climate Zone, City	Desiccant Regeneration (DR)		Water Heating (WH)		Space Heating (SH)	
	% of DR Load Met by Waste Heat Recovery		% of WH Load Met by Waste Heat Recovery		% of SH Load Met by Waste Heat Recovery	
	R-404A	CO_2	R-404A	CO_2	R-404A	CO_2
1, Miami	46.0	60.9	85.7	93.9	46.3	64.7
2A, Houston	46.4	62.9	86.6	95.5	38.6	52.8
2B, Phoenix	53.3	77.2	94.7	99.4	49.2	60.6
3A, Atlanta	46.4	64.1	86.6	94.2	32.1	41.2
3B, Los Angeles	41.8	59.9	88.0	99.0	48.3	69.0
3B, Las Vegas	58.5	87.9	91.1	97.7	35.4	44.9
3C, San Francisco	84.9	94.1	83.9	99.0	32.2	48.7
4A, Baltimore	46.2	62.5	83.7	90.3	23.6	28.7
4B, Albuquerque	42.7	60.1	86.7	92.9	27.4	32.5
4C, Seattle	41.9	59.3	81.1	93.1	22.1	29.5
5A, Chicago	46.6	63.6	82.0	85.9	19.5	22.0
5B, Boulder	46.2	64.9	83.9	89.0	22.5	26.0
6A, Minneapolis	47.4	64.8	81.6	83.6	16.9	18.0
6B, Helena	--	--	81.2	84.5	17.7	19.6
7, Duluth	42.8	60.8	78.8	81.0	14.6	15.5
8, Fairbanks	39.9	59.0	78.2	78.2	10.6	11.0

In general, the waste heat from the transcritical CO_2 booster system satisfies more of the heating requirements of the supermarket than does that of the R-404A multiplex DX system. For desiccant regeneration, the CO_2 system satisfies, on average, 67% of the heating requirements while the R-404A multiplex DX system satisfies only 49% of the heat requirements. The CO_2 system can meet approximately 91% of the water heating requirements of a supermarket while the R-404A multiplex DX system satisfies 85% of the water heating needs. Finally, the CO_2 system can satisfy 37% of the space heating load of the supermarket while the R-404A multiplex DX system satisfies 29% of the space heating.

6. CONCLUSIONS

In this paper, the whole building energy modeling tool, EnergyPlus, was used to investigate the energy consumption of a supermarket utilizing packaged rooftop air conditioning units and a transcritical CO_2 booster refrigeration system. The potential for waste heat utilization for application in desiccant regeneration, water heating and space heating was analyzed. Finally, the waste heat utilization potential of the transcritical CO_2 booster refrigeration system was compared with the baseline R404A multiplex direct expansion system in sixteen cities from eight climate zones of the United States.

In general, the ability of waste heat recovery to satisfy supermarket water heating and space heating requirements was found to decrease from the warmer climate zones to the colder climate zones. It was also found that the ability to recovery waste heat for desiccant regeneration was a function of both the annual average temperature and the annual average humidity. Cities with high temperature and low humidity were able to satisfy desiccant regeneration loads more readily than cities with higher humidity.

Using the waste heat recovery scheme (i.e., desiccant regeneration, water heating and space heating), it was found that for a supermarket ambient humidity of 55%, the CO_2 transcritical booster system could provide, on average, 67% desiccant regeneration heating, 91% water heating and 37% space heating. Lowering the store humidity to 35% reduced the CO_2 booster system's heating capability. At 35% RH, the CO_2 booster system could provide 54% desiccant regeneration heating, 85% water heating and 29% space heating. Furthermore, the average desiccant heating required to maintain 35% store RH was found to be nearly four times greater than that required to maintain 55% store RH.

In general, the waste heat from the transcritical CO_2 booster system satisfies more of the heating requirements of the supermarket than does that of the R-404A multiplex DX system. For the waste heat recovery scheme analyzed in this paper, it was found that on average, the CO_2 booster system could satisfy 65% of the supermarket's total heating needs while the R-404A multiplex system could only meet 54% of the heating requirement.

From the analysis presented, it appears that the waste heat recovery scheme (i.e., desiccant regeneration, water heating and space heating) for transcritical CO_2 booster refrigeration systems has merit. As a next step, the results of this analysis could be validated through experimentation by designing a lab-scale implementation of the proposed scheme, whereby the proper sizing and control of the waste heat recovery components are determined.

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